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# Control of ONB by Dynamic Actuation: An Open Question

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***Abstract*** **–** The effect of boiling and cavitation phenomena on nucleation was first experimentally studied considering a narrow space with one of the walls dynamically deformed. A huge decrease of the wall superheat at the nucleation incipience is obtained, especially for high amplitude and frequency of the stationary wave of deformation. Results highlight the fact that the "classical" theory of nucleation cannot describe such a configuration. It is proposed that he dynamic and the hysteresis of the contact angle may play a significant role in nucleation by simultaneous boiling and cavitation effects.

***Keywords*****:** heat transfer enhancement, wall morphing, dynamic deformation, Onset of Nucleate Boiling (ONB)

## 1. Introduction

Numerous heat transfer enhancement techniques have been developed to meet the growing need in terms of heat transfer and of compactness. Those implementing the liquid-vapor phase-change are promising. However, one of the major constraints such process is the high temperature to be achieved for the onset of the boiling (ONB). A technique for controlling the nucleation incipience temperature was proposed by Léal et al. [1, 2, 3]. It consists in simultaneously involving boiling and cavitation, using the dynamic deformation of a confinement wall. Indeed, nucleation can be obtained in two ways: by increasing the liquid temperature at constant pressure (boiling) or by decreasing the liquid pressure at constant temperature (cavitation): a decrease in pressure would then cause the decrease of the temperature necessary to reach the nucleation incipience. Furthermore, if the mechanisms governing nucleation were already studied from the "boiling" point of view and "cavitation" one, the simultaneous action of these two effects on the nucleation has not been analyzed yet.

## 2. Experimental Results

An experimental device was developed to study nucleation incipience induced by the dynamic deformation of a confinement wall. As reported on figure 1, inthe test section, a fluid (n-pentane) is confined between a heated wall and a confinement wall. The confinement wall is dynamically deformed at its centre by a piezoelectric actuator whereas its periphery is fixed. The dynamic deformation yields to successive acceleration and deceleration of the confined liquid: the liquid pressure oscillates and is thus temporally decreased. So, boiling and cavitation processes are simultaneously involved. Furthermore, the heated wall is instrumented by ten thermocouples and is polished to obtain ruggedness of about 0.2 μm. The experimental protocol consists in applying successive steps of heat flux on the heated wall and waiting between each step until the system reaches the stationary state. The nucleation incipience superheat is defined as the difference between the maximum temperature of the heated wall and the saturation temperature at ambient pressure: $\Delta T_{ONB}=T_{w,max,ONB} - T_{sat}(p_{atm})$.
It is determined by the sudden decrease of the heated wall temperatures and by the appearance of bubbles at the periphery of the confined space. Detailed explanations about the experimental device and protocol were given in previous papers [1, 4].

The nucleation incipience superheats when the dynamic deformation is imposed to the confinement wall were measured experimentally and typical results are illustrated on the following figure that shows clearly the strong impact of confinement wall dynamics on onset of boiling.

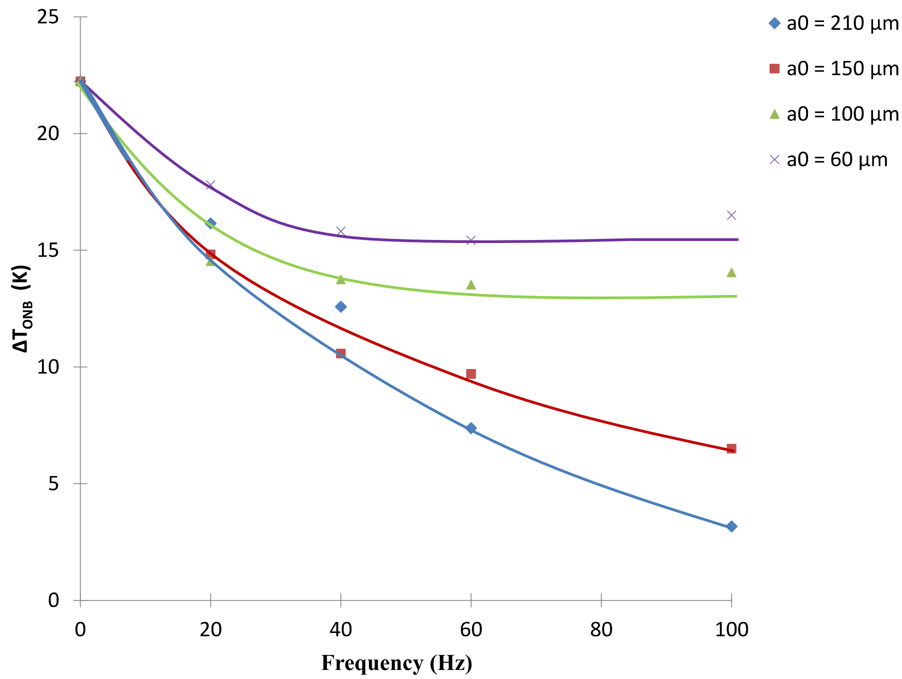


Fig. 1: Variation of the wall superheat at the Onset of Nucleate Boiling as a function of the frequency imposed to the piezoelectric actuator for different amplitude of membrane deformation.

Changes in wall superheat at ONB obtained experimentally as a function of frequency and amplitude of the dynamic deformation of the containment wall are shown in Figure 1. The wall superheat is defined as the difference between the temperature of the heated wall and the saturation temperature at ambient pressure. For ranges of amplitudes and frequencies of interest, the wall superheat at ONB decreases as the frequency and the amplitude increases. The maximum ONB superheat reduction is important (nearly 86%) and is achieved for the maximum considered amplitudes and frequency (210 µm, 100 Hz). However, for amplitudes equal to 60 and 100 µm, increasing the frequency above values respectively equal to 40 and 60 Hz does not seem to have any effect on the wall superheat at ONB anymore.

Experimental nucleation superheats were compared with those obtained by the "classical" theory of nucleation (see [4]for details). For this we need to know the minimum pressure reached in the narrow gap between the heated wall and the confinement wall over time. We thus set up a hydrodynamic model to obtain this minimum value of the pressure as a function of the dynamic deformation parameters as well as of the level of confinement [1, 3]. This model compare well with 3DCFD simulation of fluid flow in such actuated narrow channel.

Using this model, it is possible to determine the effect of the minimum value of pressure reached over time on nucleation incipience superheat.

The situation considered by the existing theory of nucleation consists in a vapour embryo attached at the aperture of the cavity of the heated wall ($r_c$=0.2 µm). The liquid pressure considered is the minimum pressure reached over time (static theory). The theoretical superheats at the onset of nucleation are determined using the following equation [4]:

$$r_c = \frac{2\sigma}{-p_l + p_{sat}(T_l)e^{\frac{v_l(p_l - p_{sat}(T_l))}{RT_l}}} \quad (1)$$

where $r_c$ is the aperture radius of the cavity, $\sigma$ is the surface tension, $p_l$ is the calculated minimum pressure over time, $v_l$ is the specific volume of the liquid, $p_{sat}(T_l)$ is the saturation pressure at the temperature $T_l$, and R is the ideal gas constant.

The comparison between the experimental and theoretical incipience superheats are compared in Figure 2. As expected, the calculated nucleation superheat decreases with decreasing the minimum value of liquid pressure. Nevertheless the predicted values do not translate in anyway the experimental findings.

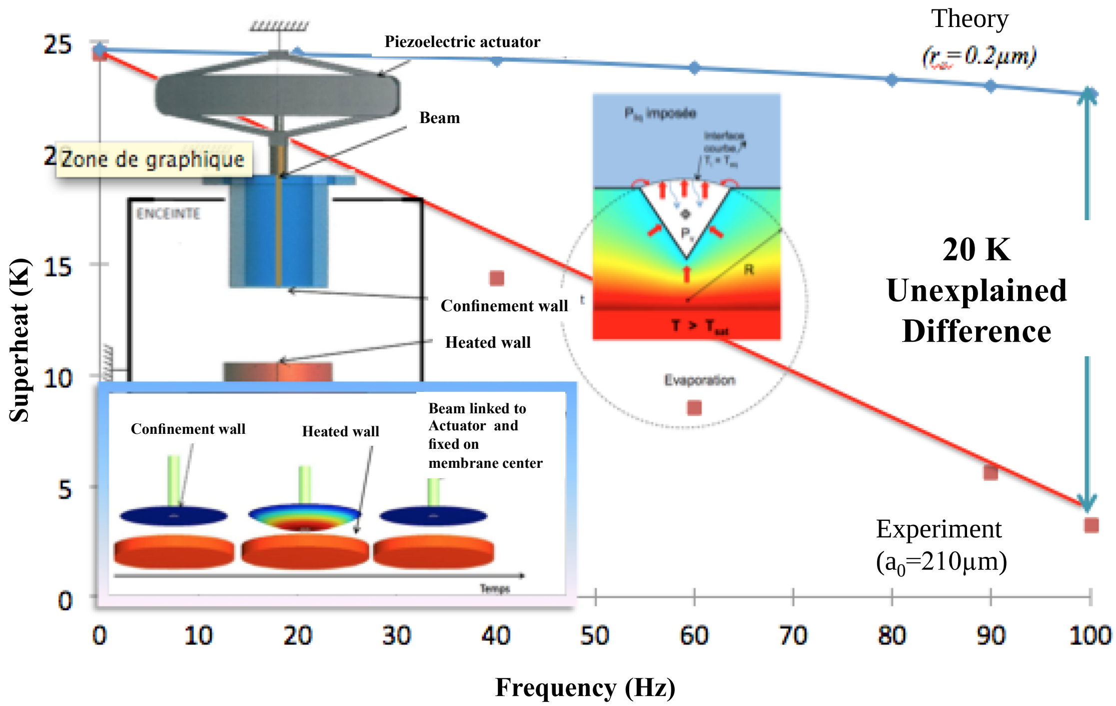


Fig. 2: Variation of the wall superheat at the Onset of Nucleate Boiling as a function of the frequency imposed to the piezoelectric actuator: comparison between experimental and theoretical results. The theoretical results are obtained considering a quasi-static assumption (Eq. 1). A sketch of the experimental setup and of the confinement wall deformation cycle is superimposed.

When the confinement wall is not deformed, the experimental nucleation incipience superheats are consistent with those theoretically obtained. On the other hand, when the dynamic deformation is imposed to the confinement wall, large discrepancies appear between the theoretical and experimental nucleation superheats. Thus, dynamics phenomena, which promote nucleation, seem to be not taken into account by the "classical" theory of nucleation.

## 3. Tentative of Explanation

Maintaining the hypothesis of an embryo attached to the aperture of the cavity, which provides satisfactory results considering the existing theory in the static case, a transient model was developed to analyse the effect of the heat flux and of the pressure oscillation on the onset of nucleation (detailed in [5]). The pressure variations over time are imposed far from the embryo, because experimentally these changes are induced by the dynamic deformation of the confinement wall.

At the scale of the embryo (characteristic dimension less than 0.2 µm), the fluid velocity at the wall due to the dynamic deformation is almost zero, assuming nonslip condition on liquid solid surfaces. The oscillation of the liquid pressure over time and the phase change (vaporisation or condensation) induce volume variations of the embryo: the curvature radius of the liquid/vapour interface is changed which causes movement of the liquid surrounding the embryo.

To model the thermal couplings between the liquid, the vapour, and the interface, the thermal diffusion and the heat transport in the liquid and within the surrounding solid are also taken into account.

Obtained results demonstrated that liquid inertia has no significant effect on the evolution of the embryo over time. In addition, the thermal equilibrium between the embryo and the solid wall is not affected by pressure oscillation. The temperatures of the vapor and of the interface are therefore constant. So the model suggests that, for the range of parameters studied, only the mechanical non-equilibrium of the interface in a quasi-isothermal environment seems to govern the embryo instability. Indeed, in the considered configuration, the contact line is assumed being attached to the aperture of the cavity wall and this point is a strong assumption. Assuming that the contact line is no longer attached, effects of the contact angle hysteresis with surface displacement should clearly change the nucleation condition.

In static situation, the contact angle is equal to the static contact angle. By imposing an external action, the volume of the embryo change. For example, let us consider the case of an increasing volume of the embryo. Firstly, the contact line remains unmoving while the value of the contact angle decreases down to be equal to the receding contact angle (limit of the hysteresis contact angle range). In the case where the volume continues to increase, the contact line begins to move within the cavity: the liquid frontline goes back. Thus, the contact line moves at a certain velocity, which leads to modify the value of the contact angle. This dissymmetry in the contact line velocity could be a starting point to explain the experimental results and the unexpected variation of ONB superheat obtained.

## 4. Conclusion

Boiling is a way implemented in the heat transfer enhancement techniques due to the high heat flux/heat transfer coefficient that can be reached. However, the onset of boiling usually requires high wall superheat. A technique to control the onset of nucleation is proposed. It consists in the dynamic deformation of a confinement wall, which induces oscillations of the liquid pressure over time. This technique allows obtaining nucleation by simultaneous cavitation and boiling and to control the amount of superheat to the boiling incipience.

The original developed experimental device shows the efficiency of this technique: the temperature required to boiling incipience is greatly decreased (up to 86 %). In addition, the physical mechanisms involved in this configuration differ from those predicted by existing theories of nucleation: some dynamic effects have a major effect on the conditions of nucleation. The effects of the dynamic and the hysteresis of the contact angle on the nucleation incipience conditions can be dominant mechanisms of nucleation by simultaneous action of boiling and cavitation. Nevertheless, further theoretical and experimental studies are required in this subject in order to better understand their effect on nucleation

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